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Modeling the Impact of Desert Aerosols on the Solar Radiation of a Mini Solar Central Photovoltaic (PV)

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Abstract

This work focuses on modeling the impact of desert aerosols on a mini central solar photovoltaic (PV). Our studied physical model is comparable to a multilayer. We have described and discretized the mathematical equations which govern the physical model. Also, we analyzed the influence of the parameters τ_a and X on the solar radiation received at the surface of solar PV modules. The results of the study taken from Figures 6(a)-(d) representing the variations of the global solar radiation on the solstices and equinoxes as well as the 21 of the months of the year days understood show that: if $\tau_a = 0$ and $X = 0$, $I_C = 67.87\%$; if $\tau_a = 0.5$ and $X = 0.5$, $I_C = 21\%$; if $\tau_a = 0.8$ and $X = 0.8$, $I_C = 12\%$ and if $\tau_a = 1.5$ and $X = 1.5$ then $I_C = 4\%$. These results show that desert aerosols significantly influence the global solar radiation received. Unfortunately, this influence lowers the productivity of the central solar PV in general.

Keywords

Modeling, Solar Radiation, Desert Aerosol, Photovoltaic Field

1. Introduction

The desert aerosols are soil particles suspended in the atmosphere in regions with easily degradable arid soils, sparse vegetation and strong winds [1] [2] [3]. These aerosols represent one of the most important features in terms of mass and optical depth and can have a significant impact on solar radiation during high dust cloud events or even in the monthly and annual average [4] [5] [6].

Burkina Faso, as a Sahelian country, is swept each year by sheets of migratory dust with an average optical depth of 0.8 μm, coming from the foothills of the Saharan mountains. Therefore, visible solar radiation is disturbed when passing through the Earth's atmosphere and in contact with a PV field. The composition of the atmosphere and the state of the central solar PV field can be considered as time and scale variables. Rigorous modeling of the radiance received by a solar field would require knowing a priori all the parameters τ_a and X related to the state of the atmosphere and to the surface of the PV field. Many experimental and numerical works had been carried out on the subject. It is known, for example, that dust can cause attenuation of solar PV radiation of around 90% [7] [8]. In contrast, little is known about the impact of desert aerosols on solar radiation received by solar PV systems. The purpose in this research is therefore to propose in this article the ideal model to study the impact of desert aerosols on the global solar radiation of a mini central solar PV of 40 kWp in Ouagadougou. We consider this mini central solar photovoltaic with the desert aerosol deposits and the atmosphere laden with desert aerosols as being a multilayer to model [9] [10].

2. Description of the Physical Model

The physical model studied is represented in **Figure 1**. The mini central solar PV is assimilated to a multilayer.

The physical model studied includes the optical thickness of desert aerosols in the upper atmosphere (τ_a), the thickness of the various aerosol deposits (X) and finally a glass surface representing the solar PV field ($S = 234\ m^2$). The principle consists in observing τ_a and X on the electrical production of the mini central solar PV. Thus, the optical properties for each layer are shown in **Figure 2**.

The solar radiation which encounters aerosol particles undergoes transformations either by absorption, diffusion and emission [11]-[16]. For this, we consider the graph of **Figure 2** of the optical model studied, which characterizes the dusty atmosphere (layer 1) in contact with dust deposits (layer 2) on the glazing (layer 3) of the PV solar field. The layer 3 is doesn't take account in this numerical studies.

Thus, **Figure 2** of the optical model shows that the solar intensity I_0 passes through layer 1 at an incident angle θ, of optical air mass m_a and optical depth of aerosols τ_a. Layer 1 and 2 respectively represent the suspension of desert aerosols in the atmosphere [17] [18] [19] and the deposition of desert dust whose deposition

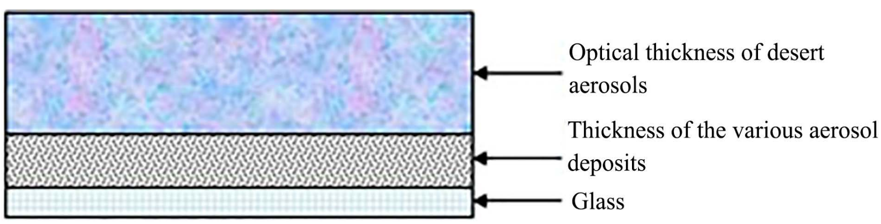


Figure 1. Studied physical model.

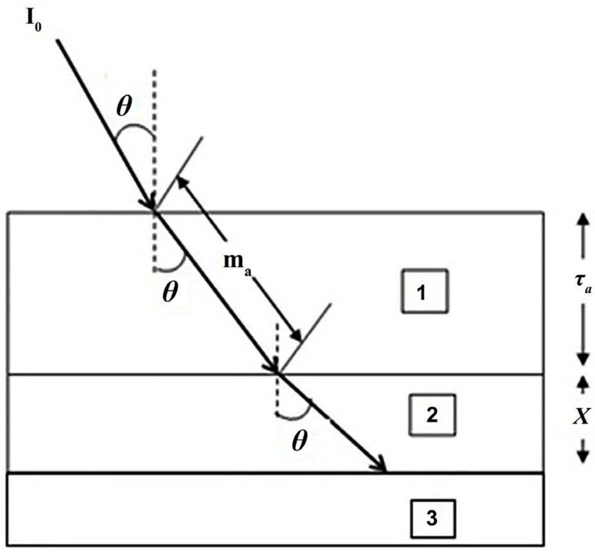


Figure 2. Optical poperties of the studied physical model.

thickness on the PV solar field is X. Layer 2 is crossed by a solar intensity I_0 at an incident angle θ.

3. Mathematical Formulation of the Studied Physical Model and Numerical Method Resolution

We have established the mathematical equations that govern our studied physical model. Thus, the clear sky radiation reaching the surface of the Earth (normal to the rays) is given by a commonly used model by treating the attenuation as an exponential decay function. The transmittance due to this multilayer is given as follows:

$$F(\tau_a, X) = \alpha = \exp(-\tau_a m_a) \times \exp(-X) \tag{1}$$

Knowing the transmisttance (Equation (1)) caused by the suspension and deposits of desert aerosols, direct radiation can be written:

$$I_{BC} = I_0 \times \cos\theta \times \exp(-m_a \tau_a) \times \exp(-X) \tag{2}$$

The final equation for direct solar radiation in a multilayer is:

$$I_{BC} = I_0 \times \left[A \sin(H_{SR}) + B \times \cos(H_{SR}) + C\right] \times \exp(-m_a \tau_a) \times \exp(-X) \tag{3}$$

with the following coefficients:

$$\cos\theta = A \times \sin(H_{SR}) + B \times \cos(H_{SR}) + C;$$

$$A = \cos\delta \times \cos(90 - \Sigma) \times \sin\gamma;$$

$$B = \cos\delta\left(\cos\gamma \times \cos(90 - \Sigma) \times \sin\varphi \times \sin(90 - \Sigma) \times \cos\varphi\right);$$

$$C = \sin\delta\left(\cos\gamma \times \cos(90 - \Sigma) \times \cos\varphi + \sin(90 - \Sigma) \times \sin\varphi\right);$$

$$\gamma = \tan\delta\left((\sin\varphi / \sin\Sigma) \times \tan\Sigma - \cos\varphi / \tan\Sigma\right);$$

The expression of diffuse solar radiation is:

$$I_{DC}=F_d\times I_0\times\left(1+\cos\Sigma/2\right)\times\exp\left(-m_a\tau_a\right)\times\exp\left(-X\right) \quad (4)$$

The expression of reflected solar radiation is:

$$I_{RC}=\rho\times I_0\times\left(\sin\beta+F_d\right)\left(1-\cos\Sigma/2\right)\times\exp\left(-m_a\tau_a\right)\times\exp\left(-X\right) \quad (5)$$

Finally, the global solar radiation is:

$$I_C=I_0\times\left(I_d+I_f+I_r\right)\times\exp\left(m_a\tau_a\right)\times\exp\left(-X\right) \quad (6)$$

with:

$$I_0=CS\left[1+0.034\times\cos\left(360\times n/365\right)\right];$$

$$m_a=P/101325\left[\sin\left(h_s\right)+0.15\left(h_s+3.885\right)^{-1,253}\right]^{-1};$$

$$P=101325\times\exp\left(-0.0001184\beta\right);$$

$$h_s=\cos\varphi\times\cos\delta\times\cos\left(H_{SR}\right)+\sin\varphi\times\sin\delta;$$

$$I_d=I_0\left[A\times\sin\left(H_{SR}\right)+B\times\cos\left(H_{SR}\right)+C\right];$$

$$I_f=F_d\times I_0\left(1+\cos\Sigma/2\right);$$

$$I_r=\rho\times I_0\left(\sin\beta+F_d\right)\left(1-\cos\Sigma/2\right);$$

$$I_g=I_0\left(I_d+I_f+I_r\right).$$

The Equations (3)-(6) are solved using the Finish Differences Method (FDM). The discretization of the equations is:

$$\left(I_{i,j}^{t+1}-I_{i,j}^{t}\right)/\Delta t=\alpha\left(I_{i+1,j+1}^{t}-I_{i+1,j-1}^{t}-I_{i-1,j+1}^{t}+I_{i-1,j-1}^{t}\right)/4\Delta x\Delta y \quad (7)$$

$$I_{i,j}^{t+1}=\alpha\Delta t\left(I_{i+1,j+1}^{t}-I_{i+1,j-1}^{t}-I_{i-1,j+1}^{t}+I_{i-1,j-1}^{t}\right)/4\Delta x\Delta y+I_{i,j}^{t}$$

$$I_{i,j}^{t+1}=\left[\alpha\Delta t\left(I_{i+1,j+1}^{t}-I_{i+1,j-1}^{t}-I_{i-1,j+1}^{t}+I_{i-1,j-1}^{t}\right)+4\Delta x\Delta y I_{i,j}^{t}\right]/4\Delta x\Delta y \quad (8)$$

Direct solar radiation:

$$I_{BC}\Big|_{i,j}^{t+1}=\left[\alpha\Delta t\left(I_d\Big|_{i+1,j+1}^{t}-I_d\Big|_{i+1,j-1}^{t}-I_d\Big|_{i-1,j+1}^{t}+I_d\Big|_{i-1,j-1}^{t}\right)+4\Delta x\Delta y\, I_d\Big|_{i,j}^{t}\right]/4\Delta x\Delta y \quad (9)$$

Diffuse solar radiation:

$$I_{DC}\Big|_{i,j}^{t+1}=\left[\alpha\Delta t\left(I_f\Big|_{i+1,j+1}^{t}-I_f\Big|_{i+1,j-1}^{t}-I_f\Big|_{i-1,j+1}^{t}+I_f\Big|_{i-1,j-1}^{t}\right)+4\Delta x\Delta y\, I_f\Big|_{i,j}^{t}\right]/4\Delta x\Delta y \quad (10)$$

Reflected solar radiation:

$$I_{RC}\Big|_{i,j}^{t+1}=\left[\alpha\Delta t\left(I_r\Big|_{i+1,j+1}^{t}-I_r\Big|_{i+1,j-1}^{t}-I_r\Big|_{i-1,j+1}^{t}+I_r\Big|_{i-1,j-1}^{t}\right)+4\Delta x\Delta y\, I_r\Big|_{i,j}^{t}\right]/4\Delta x\Delta y \quad (11)$$

Global solar radiation:

$$I_{C}\Big|_{i,j}^{t+1}=\left[\alpha\Delta t\left(I_g\Big|_{i+1,j+1}^{t}-I_g\Big|_{i+1,j-1}^{t}-I_g\Big|_{i-1,j+1}^{t}+I_g\Big|_{i-1,j-1}^{t}\right)+4\Delta x\Delta y\, I_g\Big|_{i,j}^{t}\right]/4\Delta x\Delta y \quad (12)$$

4. Results and Discussions

We present the numerical results of the code developed on MATLAB [20] [21]. Thus, the colored bars representing the colored curves in **Figures 3-5** shows the

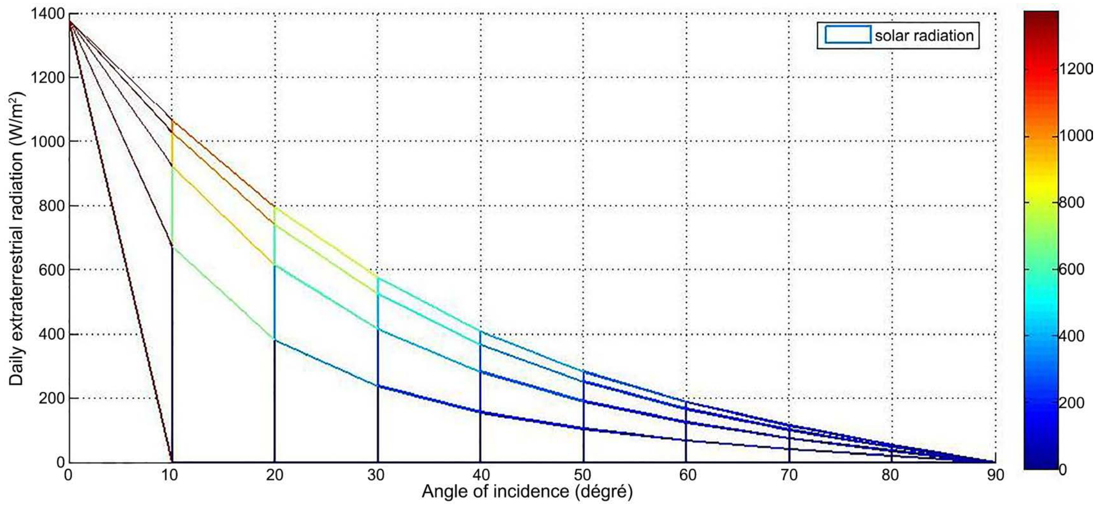
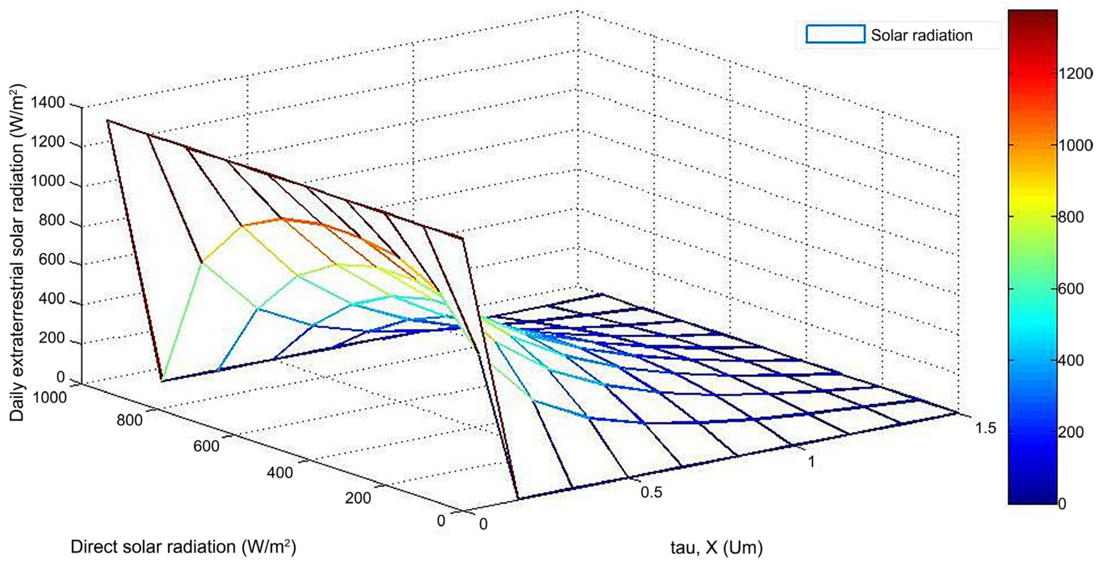
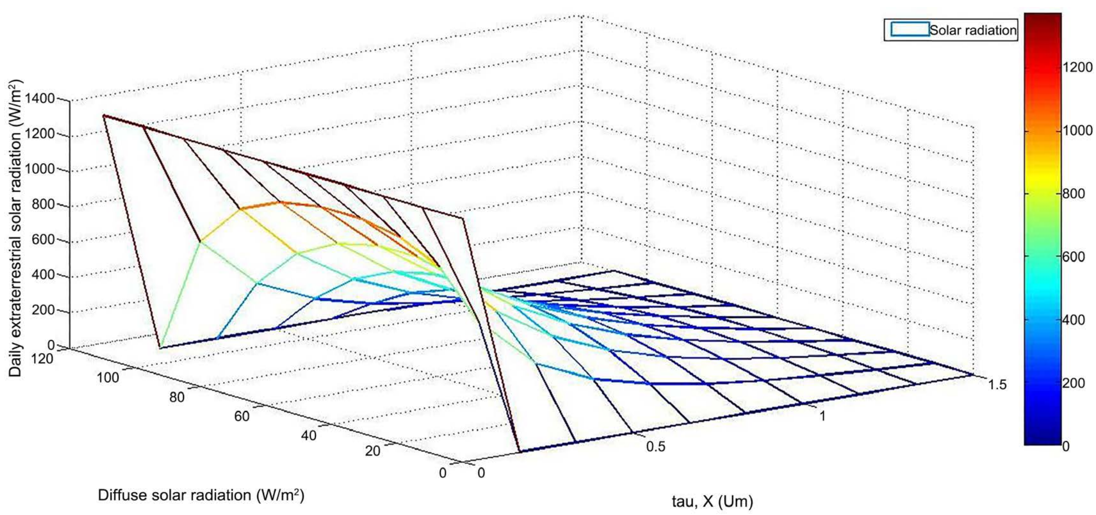


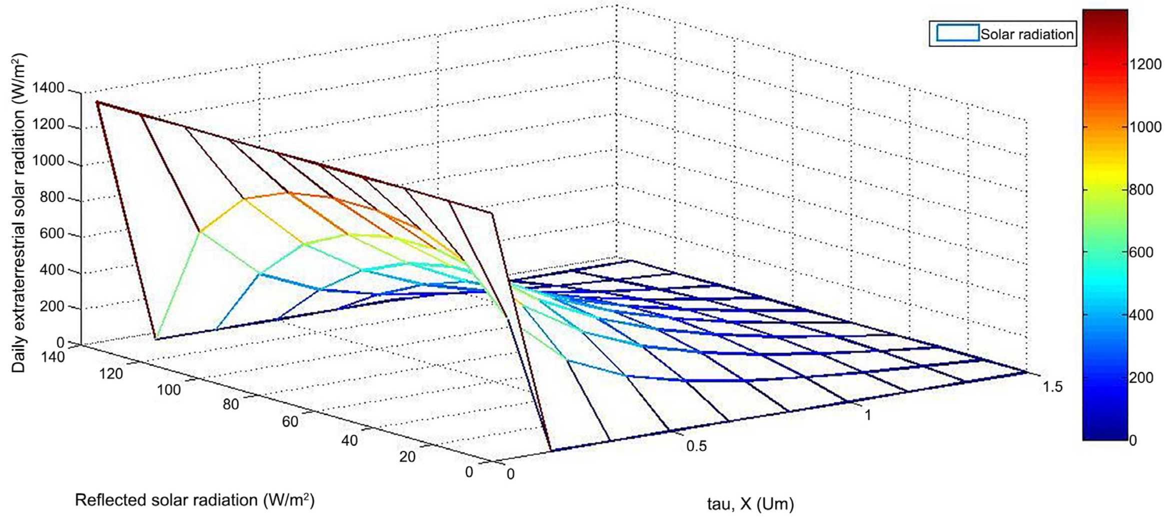
Figure 3. Variation of the solar radiation incident.



(a)



(b)



(c)

Figure 4. Variation of solar radiation: (a) direct radiation; (b) diffuse radiation and (c) reflected radiation.

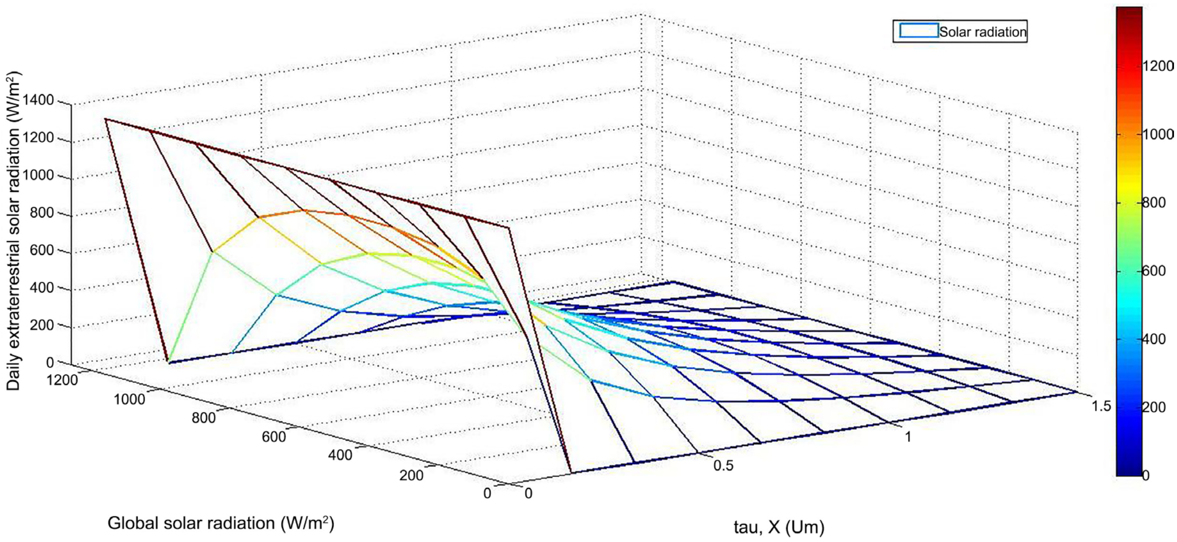


Figure 5. Variation of global solar radiation.

evolution of solar radiation (incident, direct, diffuse reflected and global) on the solar PV field. When the solar radiation is about 1400 W/m^2 on the solar field, we contact the color of the curves pulls dark red and when it is weak it tends towards 0, the color of the curves pulls towards dark blue.

4.1. Solar Incident Radiation

The curves of **Figure 3** represent the variation of the incident radiation. We find that the daily extraterrestrial solar radiation (I_0) is a function of the incident solar radiation and the angle of incidence (θ). For $\theta = 0^\circ$, the incident solar radiation is equal to the extraterrestrial solar radiation. The incident solar radiation decreases as the angle of incidence increases and at $\theta = 90^\circ$ the incident radiation is 0.

4.2. Direct, Diffuse and Reflected Solar Radiation

We present the variations of direct, diffuse and reflected solar radiation on the solar PV field. The curves of **Figures 4(a)-(c)** show that they depend on the parameters τ_a and X. We find that the solar radiation decreases when the main parameters increase by attenuating the extraterrestrial solar radiation. Indeed, if $\tau_a = 0\ \mu m$ and $X = 0\ \mu m$ this corresponds to a clear blue sky, the maximum direct solar radiation is 1000 W/m^2. When the parameters $\tau_a > 0\ \mu m$ and $X > 0\ \mu m$, the direct solar radiation (I_{BC}) decreases and tends towards 0 (**Figure 4(a)**). The diffuse solar radiation is estimated at a maximum value of 120 W/m^2 when $\tau_a = 0\ \mu m$ and $X = 0\ \mu m$. If $\tau_a = 1.5\ \mu m$ and $X = 1.5\ \mu m$ we contact that the diffuse solar radiation (I_{DC}) decreases to 0 (**Figure 4(b)**). Concerning the solar radiation reflected from the solar PV field (I_{RC}), if $\tau_a = 0\ \mu m$, $X = 0\ \mu m$, we notice that the reflected solar radiation varies and reaches a value of 140 W/m^2. The reflected solar radiation tends towards 0 if $\tau_a = 1.5\ \mu m$ and $X = 1.5\ \mu m$ (**Figure 4(c)**).

4.3. Global Solar Radiation

Figure 5 curves show the evolution over time of global solar radiation on the surface of the solar field. For the following parameters: if $\tau_a = 0$ and $X = 0$, with a cloudless sky; it can be seen that the maximum global solar radiation of the field surface is 1260 W/m^2.

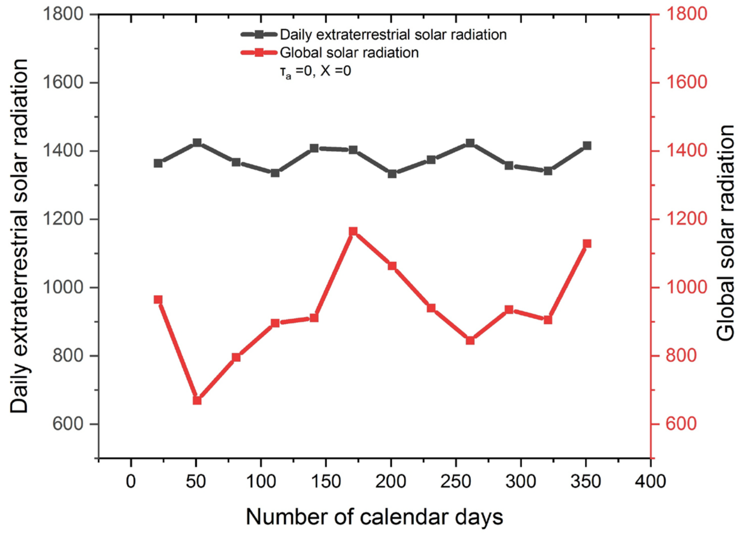
4.4. Influence of τ_a and X Thickness Constants Parameters on Global Solar Radiation and Field Solar PV

The curves in **Figures 6(a)-(d)** represent the variations of the global solar radiation on the solstices and equinoxes as well as the days 21 of the months of the year, under the influence of the parameters τ_a and X. By varying τ_a and X with a thickness of: ($\tau_a = 0$, $X = 0$; $\tau_a = 0.5$, $X = 0.5$; $\tau_a = 0.8$, $X = 0.8$ and $\tau_a = 1.5$, $X = 1.5$), we note that the global solar radiation (I_C) drops considerably from an average value of 935 W/m^2: for $\tau_a = 0$, $X = 0$ (**Figure 6(a)**) to an average value 4 W/m^2 at $\tau_a = 1.5$, $X = 1.5$ (**Figure 6(d)**). Also, we contact that τ_a and X have a negative impact on the global solar radiation of the mini central solar PV.

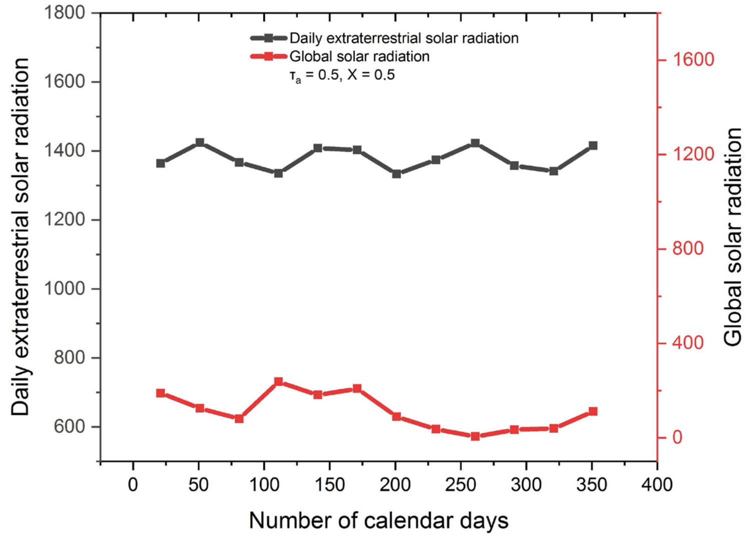
In summary, for the two parameters (τ_a and X) of our study, we give the results of the different solar radiations which cross the surface of the solar PV field. Based on the geographic data of the mini central solar PV site. We have an average daily solar time of 12.25 hours or an annual solar time of 4476 hours. The **Table 1** shows the values of solar radiation received by the mini central solar PV at $\theta = 0$.

Table 1. Maximum solar radiations of the central solar PV.

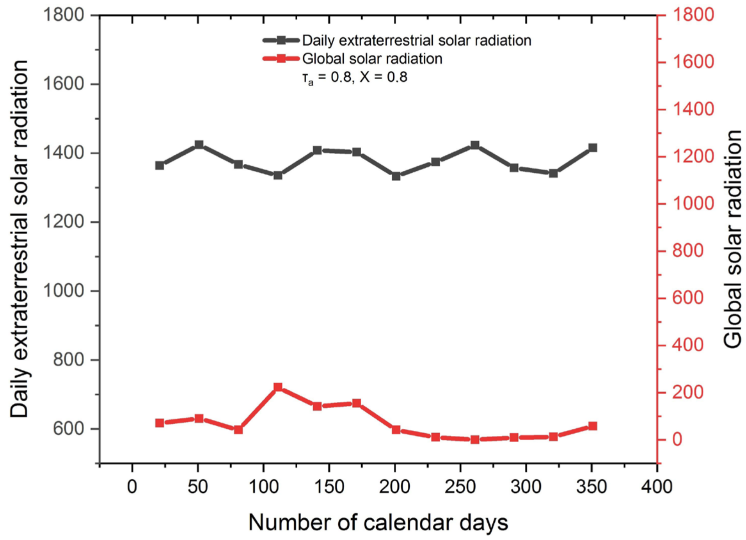
Solar radiations	Extraterrestrial	Direct	Diffuse	Reflected	Global
W/m^2	1400	1000	120	140	1260


Daily extraterrestrial solar radiation
Global solar radiation
τa =0, X =0
Daily extraterrestrial solar radiation
Global solar radiation
Number of calendar days
0
50
100
150
200
250
300
350
400
600
800
1000
1200
1400
1600
1800

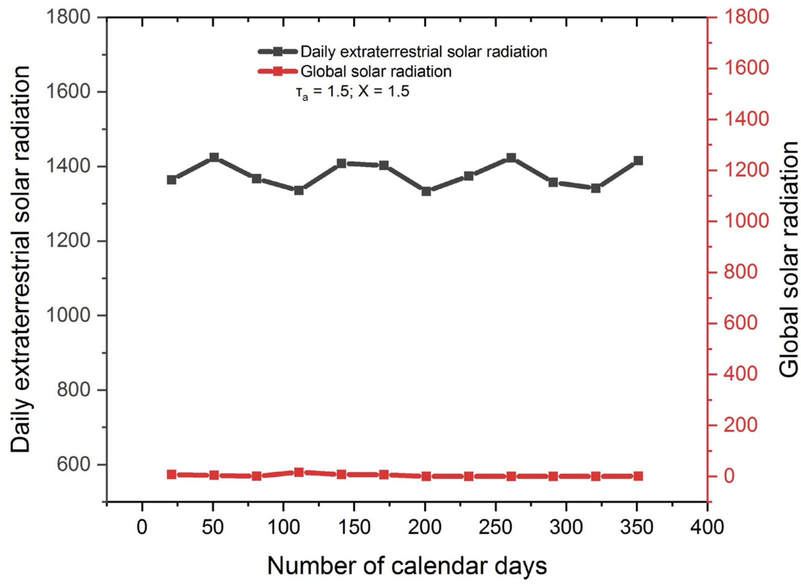
(a)


Daily extraterrestrial solar radiation
Global solar radiation
τa = 0.5, X = 0.5
Daily extraterrestrial solar radiation
Global solar radiation
Number of calendar days
0
50
100
150
200
250
300
350
400
600
800
1000
1200
1400
1600
1800
0
400
800
1200
1600

(b)


Daily extraterrestrial solar radiation
Global solar radiation
τa = 0.8, X = 0.8
Daily extraterrestrial solar radiation
Global solar radiation
Number of calendar days
0
50
100
150
200
250
300
350
400
600
800
1000
1200
1400
1600
1800
0
200
400
600
800
1000
1200
1400
1600
1800

(c)



(d)

Figure 6. Influence of τ_a and X on global solar radiation of mini central solar PV.

Finally, the quantitative study shows that out of 100% (1400 W/m²) of extraterrestrial solar radiation in the direction of the PV solar field, only 71% of this radiation is converted into direct solar radiation (I_{BC}), 10% into solar radiation reflected (I_{RC}), 9% in diffuse solar radiation (I_{DC}) and 10% of solar radiation are considered lost. Thus, global solar radiation is 90% of extraterrestrial solar radiation. According to a variable angle of incidence (θ) on the solstices and equinoxes of the year, the average global solar radiation on the solar PV field is: if $\tau_a = 0$ and $X = 0$, $I_C = 67.87\%$; if $\tau_a = 0.5$ and $X = 0.5$, $I_C = 21\%$; if $\tau_a = 0.8$ and $X = 0.8$, $I_C = 12\%$ and if $\tau_a = 1.5$ and $X = 1.5$ then $I_C = 4\%$

5. Conclusion

At the end of our study on the influence of desert aerosols on the mini central solar PV, we described the mathematical equations which govern the system of the studied physical model. Then, these equations are discretized using a Finite Difference Method and solved by the Gaussian algorithm. The numerical results show that if $\tau_a = 0$ and $X = 0$, with a cloudless sky; we have a maximum global solar radiation at the surface of the PV solar field of 1260 W/m². This value of global solar radiation indicates a very significant improvement in the productivity of the mini central solar. And if $\tau_a = 1.5\ \mu\text{m}$ and $X = 1.5\ \mu\text{m}$, the global solar radiation tends towards very low values (<10 W/m²). This shows a low productivity of the mini central solar PV. Finally, the parameters τ_a and X considerably influence the operation of the mini central solar PV. We showed that our numerical results on the desert aerosols can be to influence the central solar PV productivity in West Africa countries. From a theoretical point of view, this modeling research has enabled us to establish a new model for evaluating the impacts of desert aerosols on the radiation received by a solar PV system. It is a true model that solves all cases of issues that deal with mineral dust deposits and suspensions on solar PV systems. Our numerical method consisted of the desert aerosols on global solar radiation, another digital method could have consisted of showing the impact of gaseous aerosols on solar radiation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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